The Intercomparison of Satellite-Derived and *In Situ* Profiles of Droplet Effective Radii in Marine Stratocumulus Clouds

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***Abstract*—It was found that the satellite spectral measurements can be used not only for the determination of cloud top effective radii but also for retrieving the effective radii vertical profile in some specific cases (e.g., for low marine stratocumulus clouds with negligible effects of horizontal variability). The inversion algorithm was applied to Moderate Resolution Imaging Spectroradiometer (MODIS) radiances (at the wavelengths of 0.865, 1.24, 1.6, and 2.1 μm), and the results were validated against *in situ* airborne measurements of cloud vertical profiles of the effective radius. We found that the results were more reliable for the cases with large vertical gradients of droplet sizes. The new retrieval method, based on the optimal estimation approach, enabled a higher accuracy of the liquid water path estimate than that produced with the standard MODIS vertically homogeneous algorithm.**

***Index Terms*—Airborne measurements, cloud remote sensing, effective radius, liquid water path (LWP), Moderate Resolution Imaging Spectroradiometer (MODIS).**

I. Introduction

TERRESTRIAL clouds are vertically inhomogeneous objects, and yet, modern operational cloud retrieval algorithms are based on the assumption that a cloud can be represented as a homogeneous plane-parallel light scattering layer. This enables the simplification of the retrieval algorithms. In particular, two-channel algorithms can be used to infer the liquid water path (LWP) and the effective radius of droplets or crystals [1], [18], [13], [8]. The fundamental problem of such approach is the fact that the derived quantities are functions of the selected satellite channels, and therefore, effective radii retrieved from pair of channels such as 0.865/1.6 μm and 0.865/2.1 μm are not equivalent. It also means that the spectral reflectance function derived using the retrieved cloud parameters coincides with the measured one only in selected number of spectral points (for example, at 0.865 and 1.6 μm and not at 2.1 μm). That is to say, the homogeneous cloud model cannot be used to provide a good quality fit for all channels in the case of realistic vertically inhomogeneous cloudy media [7]. Clearly, this is unsatisfactory, and a new approach must be developed, where the measurements performed at all channels can be described accurately by the radiative transfer calculations.

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Chang and Li [2], [3], Wang *et al.* [19], Kokhanovsky and Rozanov [9], and also King and Vaughan [5] proposed to derive cloud properties using not just two channels but also several of them (e.g., centered at 0.645, 0.865, 1.24, 1.64, 2.13, and 3.75 μm). Such a global fit can be performed and be very accurate, only if the assumption on the cloud vertical structure is relaxed. This new remote sensing technique based on the assumption of a vertically inhomogeneous cloud enables the determination of the cloud vertical structure using passive multi- and hyperspectral satellite measurements, which is an important topic of modern cloud research. The use of polarization of reflected light and also multiviewing instrumentation makes the retrievals even more accurate and robust. There are various practical strategies for the solution of the problem. In particular, Chang and Li [2], [3] and Wang *et al.* [19] used the common lookup-table method, where the spectral reflectances were precalculated for a range of profiles and then a numerical iterative technique was used to determine the cloud vertical droplet size profile. Kokhanovsky and Rozanov [9] developed the retrieval method based on the optimal estimation technique, where the radiative transfer calculations are performed enabling the determination of arbitrary vertical profiles. The approach does not use the lookup tables, and therefore, the developed technique is very flexible and can be applied to any required combination of channels, observation geometries, cloud vertical droplet size profiles, and type of sensor.

The simplest case of the vertical droplet size profile is a linear one. Although this assumption is a simplification of the reality, it is a clear step forward as compared to the homogeneous cloud, where just one size of droplets is used to represent the whole cloud volume. From the physics of the problem, one may expect that the larger droplets are present at the cloud tops for nonprecipitating marine stratocumulus clouds, which are the subject of this work.

The main objective of this letter is to perform the intercomparison of *in situ* and satellite-derived cloud properties such as the cloud droplet vertical profile and LWP under the assumption of a linear vertical droplet size profile. The case of a nonlinear profile was studied in the framework of the optimal estimation method by King and Vaughan [5]. However, the way they solve the problem (and the wavelengths selected) is different from that used by us. In particular, they derive the effective radius as the function of the optical (and not geometrical) depth.

II. *In Situ* Measurements

The vertical profiles of cloud microphysics were collected off the Chile coast during the Variability of the American Monsoon Systems (VAMOS) Ocean-Cloud-Atmosphere-Land Study Regional Experiment (VOCALS-REx [20]). The spatial

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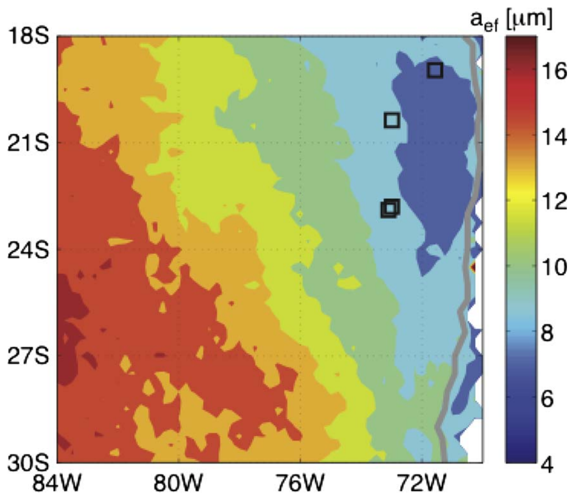

Fig. 1. Spatial distribution of the mean MODIS cloud effective radius a_{ef} retrieved from the 2.1-μm reflectance for the period October–November 2008 in the region 18–30 S longitude and 71–84 W latitude. The black squares correspond to the location of the four aircraft vertical profiles used in this study. The gray line indicates the coastal line.

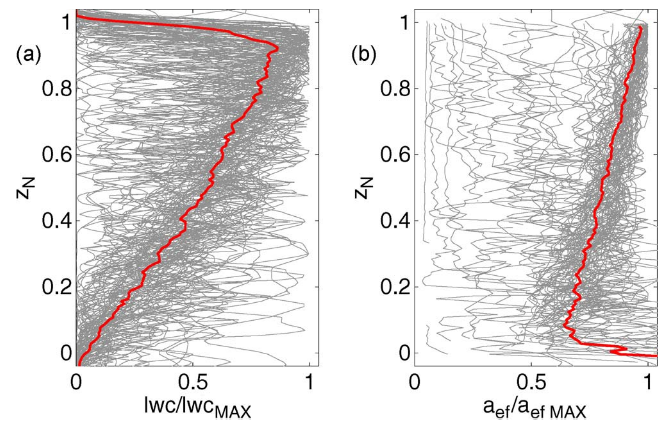

Fig. 2. Cloud vertical profiles collected by the aircraft C-130. (a) Normalized profiles of lwc. (b) Normalized profiles of a_{ef}. $Z_N = 0$ indicates the cloud base, whereas $Z_N = 1$ indicates the cloud top. Red lines correspond to the median profiles. This figure is modified from [14].

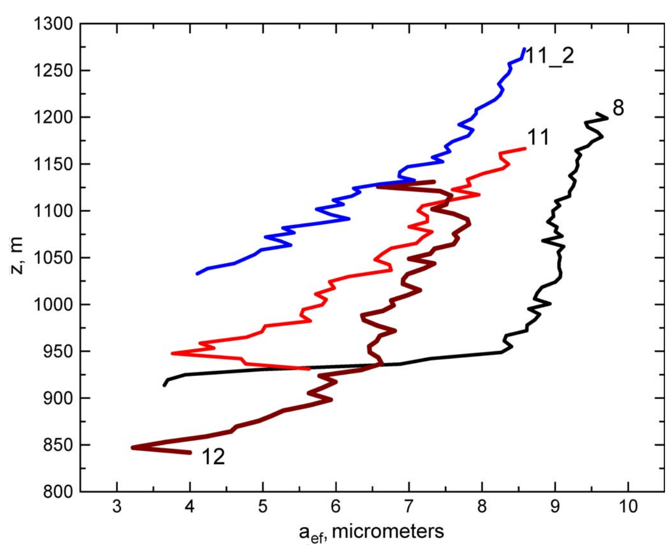

Fig. 3. *In situ* cloud effective radius profiles analyzed in this study. The numbers near each profile correspond to cases in Table I.

distribution of the cloud top droplet effective radius for the same region, as derived from satellite data using Moderate Resolution Imaging Spectroradiometer (MODIS) standard retrieval algorithm [4], is shown in Fig. 1. This region presents one of the most persistent and extended marine stratocumulus regimes on the planet [6] and, therefore, provides favorable conditions for remote sensing of cloud effective radius and optical thickness. This cloud regime is formed over a region with low sea surface temperatures due to ocean upwelling and capped by a strong subsidence that produces a temperature inversion above the cloud top. *In situ* and satellite retrievals reveal a distinctive cloud effective radius spatial pattern, with magnitudes that decrease toward the coast, arguably associated with the effect of aerosols that are transported from the continent into the cloud deck (see Fig. 1 and [21] and references therein).

Liquid water content (lwc) and cloud effective radius were derived from the cloud droplet size distribution measured by the Cloud Droplet Probe (CDP) [10], onboard the research aircraft C-130. The samples were collected at 1 Hz, which allows resolving vertical profiles with 6 m of resolution. The accuracy of the instrument was tested against a hot wire King lwc probe. Although a small bias was found in the CDP measurements, this would translate into a mean cloud effective radius bias of 0.17 μm. This bias was minimized following the methodology described in [14]. LWP and cloud optical thickness τ were calculated by vertically integrating the lwc and volume extinction coefficient (the second moment of the droplet size distribution), respectively. It is important to note that vertically integrated quantities are more prone to instrument uncertainties than water content and effective radius measurements.

Normalized profiles of lwc show a nearly linear increase with cloud depth and a subtle decrease near the cloud top, a feature likely attributed to evaporation due to cloud top mixing [Fig. 2(a)]. Consistent with the lwc profile, the normalized effective radius monotonically increases until reaching a maximum at the cloud top [Fig. 2(b)]. Moreover, the absolute values of the effective radius encompass values between 5 and 25 μm, although they are typically smaller than 15 μm.

Here, we analyzed four near coastal vertical profiles (see Fig. 3) collocated within 15 min of the Terra pass occurrence (Fig. 1, squares). The exact MODIS pixel location was corrected by the distance traveled by the cloud during the lapsed time between the satellite pass and the vertical profile occurrence, assuming a constant velocity given by the wind speed [14]. These four vertical profiles showed the typical monotonic increase with height as shown in the graph in Fig. 3, with effective radii smaller than 10 μm. In addition, the selected profiles showed negligible drizzle, with *in situ* optical thickness exceeding 8 and cloud tops below 1300 m. The variation of droplet number concentration along the vertical coordinate was small or negligible for the considered cases. The summary of observations is given in Table I.

III. Retrievals and Intercomparison

We used MODIS Terra level 1 (10:30 local time pass) reflectances at 1-km spatial resolution (MOD21 km) to compare MODIS-derived cloud properties and *in situ* measurements. Two algorithms were used for the determination of cloud

TABLE I

RETRIEVED AND MEASURED *IN SITU* CLOUD PARAMETERS. THE FIRST LINE IN EACH ROW CORRESPONDS TO THE CASE OBS8 WITH THE CLOUD TOP AT 1204 m AND CLOUD BOTTOM AT 914 m, THE SECOND LINE CORRESPONDS TO THE CASE OBS 11 WITH THE CLOUD TOP AT 1166 m AND CLOUD BOTTOM AT 931 m, THE THIRD LINE CORRESPONDS TO THE CASE OBS 11_2 WITH THE CLOUD TOP AT 1273 m AND CLOUD BOTTOM AT 1033 m, and THE FOURTH LINE CORRESPONDS TO THE CASE OBS12 WITH THE CLOUD TOP AT 1131 m AND CLOUD BOTTOM AT 842 m. FOR THE EFFECTIVE RADIUS, MODIS GIVES THE EFFECTIVE RADII RETRIEVED AT 1.6, 2.1, and 3.7 μm, AND THEY ARE LISTED IN THE FOLLOWING ORDER: $a_{\rm ef}$ (1.6 μm), $a_{\rm ef}$ (2.1 μm), and $a_{\rm ef}$ (3.7 μm). FOR PEROMT, RADII AT THE CLOUD TOP AND BOTTOM ARE LISTED. THE RADII AT THE CLOUD TOP ARE LARGER AS COMPARED TO THE RADII AT THE CLOUD BOTTOM. THE *IN SITU* RADIUS CORRESPONDS TO THE MEASUREMENT AT THE CLOUD TOP. *IN SITU* DROPLET NUMBER CONCENTRATIONS AT THE CLOUD TOP WERE 153.21, 180.41, 164.26, AND 263.05 cm^{-3}, RESPECTIVELY, FOR THE CASES 8, 11, 11_2, AND 12 [14]. THE TIMES OF MEASUREMENTS (COUNTED FROM JANUARY 1, 2008) WERE 307.6179, 314.620, 314.581, AND 316.6069 DAYS, RESPECTIVELY, FOR CASES LISTED EARLIER

Parameter	MODIS algorithm	PEROMT	In situ
Cloud optical	18.0	18.6	17.1
thickness	11.3	12.5	8.7
	14.9	15.4	11.5
	8.5	8.4	14.3
Liquid water path,	142.8	91.3	101.8
g/m^2	68.2	57.9	39.3
	102.3	72.0	58.5
	41.5	29.8	61.9
Effective radius,	11.0, 11.9,10.3	13.0 - 4.0	9.5
microns	8.8, 9.1, 9.4	7.7 - 7.0	8.5
	8.9, 10.3, 10.3	9.9 - 5.3	8.5
	7.5, 7.3, 6.4	7.1 - 4.2	7.3

parameters: the standard MODIS Collection 5 Retrieval Algorithm (MRA) [4] and the Profile of the Effective Radius using Optimal Estimation Technique (PEROMT) [9]. MRA is based on the lookup-table approach to determine the effective radius of cloud droplets and the cloud optical thickness from the two-channel solar light reflectance measurements (in the near visible and near infrared; e.g., 0.865 and 2.1 μm). It is assumed that the cloud is a vertically homogeneous light scattering medium composed of either water droplets or ice crystals [4]. PEROMT is the retrieval method based on the optimal estimation technique. It is assumed that the unknown effective radius of cloud droplets varies along the vertical profile and the cloud is horizontally homogeneous light scattering layer composed of water droplets with known (assumed) shape of the droplet size distribution (and the effective variance). The current version of PEROMT cannot be applied to crystalline and mixed-phase clouds. The first guess solution is derived using the asymptotic radiative transfer theory [7] and two-channel algorithm (0.865 and 2.1 μm) for the assumed homogeneous cloud layer. The vertical profile of the effective radius is found by matching the measured spectral reflectance at channels 0.865, 1.24, 1.6, and 2.1 μm with the radiative transfer calculations for the variety of profiles in the framework of the optimal estimation approach. Simultaneously, the cloud optical thickness (at 550 nm) and the droplet number concentration N are derived. It is assumed that N is either constant or has a known functional dependence on the vertical coordinate. In this letter, PEROMT was applied both to MODIS data and to the synthetic top-of-atmosphere (TOA) reflectances derived using the radiative transfer calculations with SCIATRAN [17] for the cloud parameters obtained from *in situ* measurements. The synthetic TOA reflectances were similar to those measured by MODIS. The small differences can be attributed to the effects of errors in collocation between satellite and airborne measurements, incomplete information on the atmospheric state used in radiative transfer simulations, errors of measurements (noise and calibration errors), and horizontal cloud inhomogeneity effects. More details on PEROMT are given by Kokhanovsky and Rozanov [9].

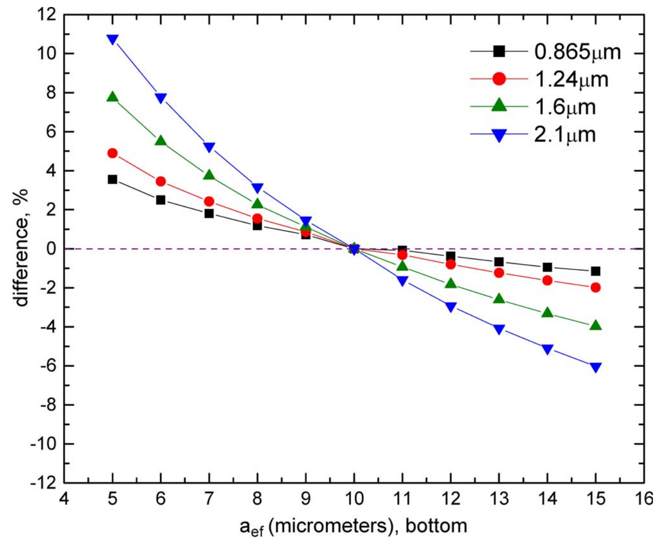

Fig. 4. Difference (in percent) in spectral reflectances of inhomogeneous clouds at channels 0.865, 1.24, 1.6, and 2.1 μm from the case of a homogeneous cloud with $a_{\rm ef} = 10$ μm. The observation is at nadir, and the solar zenith angle is equal to 60°. The cloud is positioned between 1 and 2 km. The effective radius at the cloud top is equal to 10 μm. The effective radius at the bottom changes from 5 to 15 μm as shown in the figure. All profiles are linear.

Cross-calibrations between MODIS Terra and its Aqua counterpart reveal 1% higher Terra reflectances for 0.67-μm channel relative to Aqua [12]. In addition, Terra/Aqua differences up to 5% are observed in the 1.24- and 2.1-μm channels. A preliminary analysis indicates that MODIS Terra calibration issues would account for a mean bias in effective radius of 0.5 μm over oceanic areas (Patrick Minnis, 2012; personal communication). This calibration offset in the effective radius is smaller than the observed 1–2-μm MRA effective radius bias relative to the *in situ* observations reported during VOCALS-REx (e.g., [24] and [14]). The correct calibration of the remote sensing instrument is of a particular importance for the determination of cloud droplet vertical profiles. This is due to the fact that the effects of cloud vertical inhomogeneity are small and they are generally close to the calibration errors (in particular, for small gradients of the cloud droplet radii along the vertical coordinate). This is demonstrated in Fig. 4, where we show the difference in the solar light reflectance at several wavelengths for vertically inhomogeneous cloud layers as compared to a homogeneous cloud layer with the effective radius of cloud droplets equal to 10 μm. It is assumed that the homogeneous and inhomogeneous clouds have the same optical thickness. The cloud effective

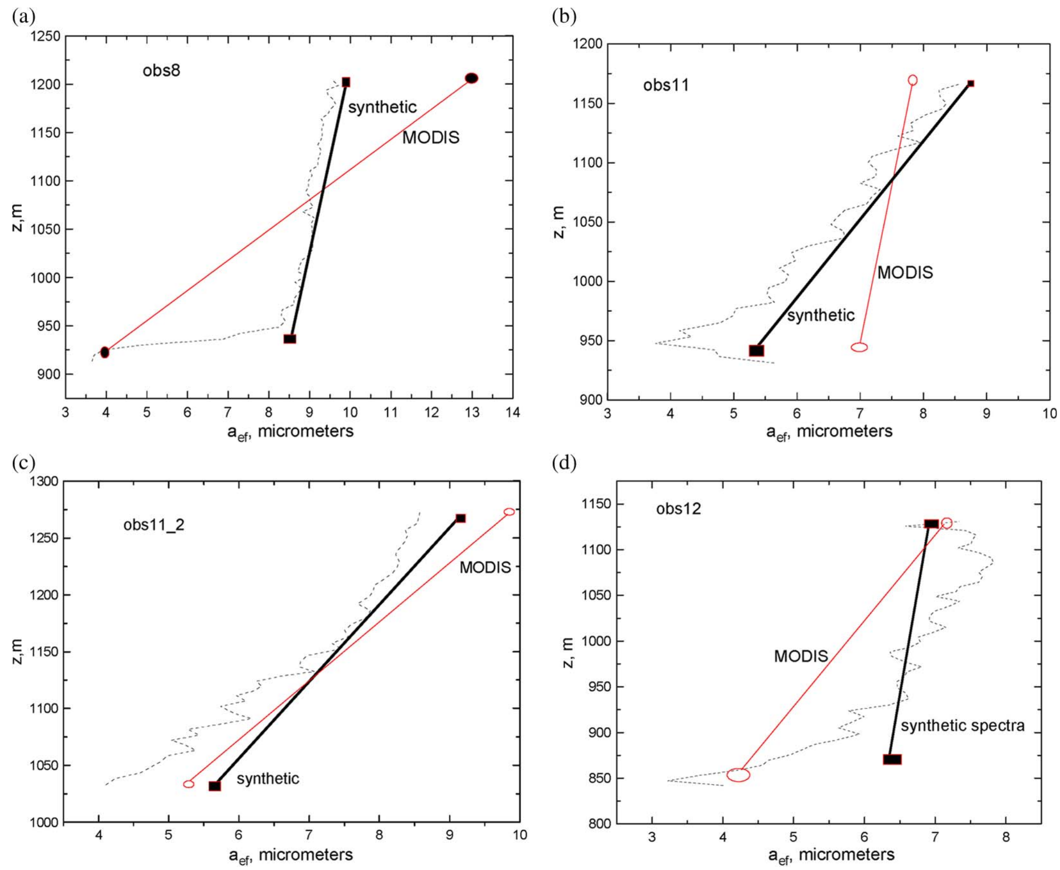

Fig. 5. (Broken lines) *In situ* and PEROMT-retrieved profiles for four studied cases. The retrievals based on the MODIS data are shown by red lines. The retrievals based on the synthetic spectral reflectances calculated from *in situ* measurements of profiles are given by thick black lines.

radius at the top is equal to 10 μm for the assumed vertically inhomogeneous cloud layers. The profiles are linear, and the effective radius changes from 5 to 15 μm at the cloud bottom for various vertically inhomogeneous cloud scenarios.

As mentioned previously, although high correlations were observed during VOCALS-REx between *in situ* observations and MRA retrievals, MRA droplet effective radius overestimated by nearly 2 μm its in situ counterpart. The factors that account for the MRA offset are not well understood yet, and they might include the following: 3-D radiative transfer effects, satellite viewing geometry, and water vapor absorption, among others (e.g., [22], [15], and [11]). Moreover, MRA-derived effective radii retrieved from the 1.6-, 2.1-, and 3.7-μm channels did not reproduce the expected vertical profile [16], i.e., the radius derived at 3.7 μm is larger than that at 2.1 μm and larger than the radius derived using the 1.6-μm channel. Instead, the radius derived from measurements around 2.1 μm was generally the largest irrespective of the cloud vertical structure [14, Table III].

The retrievals using PEROMT are shown in Fig. 5. The retrieved profiles are derived from MODIS observations and synthetic radiances generated using *in situ* profiles (Fig. 5, red and black solid lines, respectively). As expected, the algorithm is capable to correctly reproduce the decrease of cloud effective radii toward the cloud bottom. Nevertheless, the retrievals are more accurate when the synthetic radiances are used. This points to the possible MODIS calibration problem, incorrect assumption on the atmospheric state, and underlying surface reflectance needed for the PEROMT retrievals or problems with collocation/in situ measurements. In particular, we have assumed that the surface is Lambertian and its albedo is equal to 0.04. The water vapor column was assumed to be equal to 0.3 g/cm^2, which is close to the measurements at studied locations. The positions of cloud boundaries were taken from corresponding airborne measurements. We did not use MODIS measurements at 3.7 μm to reduce uncertainties related to the influence of generally unknown atmospheric state (e.g., temperature and water vapor profiles and separation of the thermal emission contribution).

The comparison of retrieved values of cloud optical thickness and LWP using remote sensing and *in situ* measurements is given in Table I. Both MRA and PEROMT give very close values of cloud optical thickness. The *in situ* values of cloud optical thickness are lower as compared to the satellite retrievals (except for the case 12). This points out to problems with *in situ* data interpretation. Disagreements between *in situ* and satellite τ might be in part attributed to errors inherent of the *in situ* vertically integrated quantities, as well as subpixel variability not representative of the *in situ* cloud vertical profile. The LWP from PEROMT is closer to *in situ* observations (except for the case 12). Generally, effective radii are consistent for all retrievals with larger deviation for the case 8. It follows from Table I that the MODIS algorithm tends to retrieve the effective droplet radii close to the values retrieved by PEROMT at the cloud top. This is consistent with the fact that the weighting function for the effective cloud droplet radius has a maximum at the cloud top [9]. Because droplet radii in reality decrease toward the cloud bottom for the case studied in this work (but

assumed to be constant by the MODIS algorithm), the LWP as derived from MODIS is overestimated (except for the case 12).

IV. Conclusion

We have compared *in situ* airborne measurements of droplet vertical profiles with those derived from multispectral MODIS measurements performed at four wavelengths: 0.865, 1.24, 1.6, and 2.1 μm. The profiles we used were nearly collocated (in time and space) with the MODIS scan. We have found that, in all cases (except case 12), the derived values of LWP are closer to *in situ* observations as compared to MODIS results. This demonstrates the importance of the determination of the profile of the effective radius for more accurate assessments of the total water amounts stored in the clouds. The optical thicknesses derived from MODIS and PEROMT are about 8.5 for the case 12 and 14.3 for their *in situ* counterpart. Thus, there is a clear discrepancy of the *in situ* and satellite results for the cloud optical thickness for the case 12, which points to possible problems of *in situ*-derived LWP for the case 12. All derived vertical profiles show the decrease of droplet sizes to the cloud bottom in concert with *in situ* observations. Therefore, the technique can be used also for the discrimination of raining (with larger sizes at the bottom) and not raining clouds. As it follows from Fig. 4, the retrievals of cases with weak vertical variations of the effective radius are hardly possible taking into account calibration errors of optical instruments and uncertainties related to incomplete knowledge of atmospheric state. Clearly, the use of multiangle and polarization measurements [7] and also the hyperspectral measurements [5] can be of help to reduce the corresponding retrieval errors. As a matter of fact, cloud properties must be derived simultaneously with all other parameters of atmospheric state including trace gas concentrations, aerosol load, and corresponding atmospheric profiles. The contribution from the underlying surface must be assessed as well.

The technique has its limitations and can be applied only to single-layered horizontally homogeneous stratocumulus clouds with considerable gradients of effective radii. Some of the discrepancies between MODIS-derived and *in situ* profiles of vertical radii shown in Fig. 5 can originate from the fact that clouds can be considered as horizontally homogeneous objects only in the first approximation [23].

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